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THE PULSE PHASE–DEPENDENT SPECTRUM OF THE ANOMALOUS X–RAY PULSAR 1RXS J170849–400910

G.L. ISRAEL[1,2], T. OOSTERBROEK[3], L. STELLA[1,2], S. CAMPANA[4,2], S. MEREGHETTI[5] AND A.N. PARMAR[3]
1. Osservatorio Astronomico di Roma, Via Frascati 33, I–00040 Monteporzio Catone (Roma), Italy, gianluca@mporzio.astro.it
2. Affiliated to the International Center for Relativistic Astrophysics (I.C.R.A.)
3. Space Science Department of ESA, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands
4. Osservatorio Astronomico di Brera, Via Bianchi 46, I–23807 Merate (Lc), Italy
5. Istituto di Fisica Cosmica "G.P.S. Occhialini" del C.N.R., Via Bassini 15, I–20133 Milano, Italy
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ABSTRACT

We report on the results of a 50 ks *Beppo*SAX observation of 1RXS J170849−400910, one of the five (plus a candidate) known anomalous X–ray pulsars. The *Beppo*SAX data are consistent with a power–law plus blackbody spectral decomposition, making 1RXS J170849−400910 the fourth source of this class for which such a spectral decomposition was found. The inferred power–law slope and blackbody temperature are $\Gamma \sim 2.6$ and $kT_{BB} \sim 0.46$ keV, respectively. We found significant energy–dependence of the pulse profile, a remarkable feature for an AXP. By using the power–law plus blackbody decomposition we detected a significant variation in at least one spectral parameter, the power–law photon index, as a function of the pulse phase. This is the first significant detection of spectral parameter variation in an AXP. The implications of these results are briefly discussed.

Subject headings: stars: neutron — pulsar: individual (1RXS J170849−400910) — pulsars: general — X–ray: stars

1. INTRODUCTION

After more than 20 years since the discovery of pulsations from 1E 2259+586 the nature of the Anomalous X–ray Pulsars (AXPs) is still an open issue. Although we can be reasonably confident that AXPs are magnetic rotating neutron stars (NSs), their energy production mechanism is still uncertain. It is also unclear whether they are solitary objects or are in binary systems with very low mass companions (for a review see Israel et al. 2001 and references therein). Different production mechanisms for the observed X–ray emission have been proposed, involving either accretion or the dissipation of magnetic energy. Among the properties that distinguish AXPs from known magnetic ($\geq 10^{12}$ G) accreting X–ray pulsars found in High and Low Mass X–Ray Binaries (HMXBs and LMXBs) are: (i) spin periods in a narrow range ($\sim$6–12 s), (ii) very soft and absorbed X–ray spectra, (iii) relatively stable spin period evolution, with long term spin–down trend, (iv) flat distribution in the Galactic plane and three clear associations with supernova remnants. There are currently five ascertained members of the AXP class plus one likely candidate.

The relatively bright source 1RXS J170849–400910 was discovered early in the ROSAT mission (Voges et al. 1996); however only in 1997 this source attracted much attention because of the ASCA discovery of $\sim$11 s pulsations (Sugizaki et al. 1997). Based on the pulse period and unusually soft X–ray spectrum the source was tentatively classified as a candidate AXP. This interpretation was confirmed through ROSAT High Resolution Imager (HRI) observations which provided the first measurement of the period derivative $\dot{P} \sim 2 \times 10^{-11}$ s s^{-1} (Israel et al. 1999a). 1RXS J170849–400910 is one of the two AXPs for which a phase–coherent timing solution was obtained by a systematic monitoring program with the *Rossi*XTE PCA (Kaspi et al. 1999). The source was found to be a quite stable rotator with phase residuals of only $\sim$1%, i.e. comparable to or smaller than those measured for most radio pulsars. However, on 1999 September the *Rossi*XTE satellite detected a sudden spin–up event from 1RXS J170849–400910 which was interpreted as a "glitch" similar to those observed in the Vela and other young radio pulsars (Kaspi et al. 2000).

A search for optical counterparts in the field of 1RXS J170849–400910 was carried out by Israel et al. (1999a). These authors, based on two refined ROSAT HRI positions, were able to rule out a massive early type companion (a distant and/or absorbed OB star would appear more reddened). However, the images were taken from a 1.5 m telescope and were not deep enough to constrain any other proposed theoretical scenario such as a low–mass companion, a residual disk or a magnetar.

An association between 1RXS J170849–400910 and the supernova remnant (SNR) G346.6–0.2 located $\sim 12'$ away was proposed by Marsden et al. (2001). However, as discussed by Gaensler et al. (2001) such an association appears to be unlikely. An image at 1.4 GHz showed the presence of an arc of diffuse emission $\sim 8'$ away from 1RXS J170849–400910 (Gaensler et al. 2001), which was interpreted as a previously unknown supernova remnant (G346.5–0.1). Also in this case there are no convincing arguments for a physical association between G346.5–0.1 and 1RXS J170849–400910. No radio emission was detected from 1RXS J170849–400910, with upper limits of 3 mJy on the continuum (5σ at 1.4 GHz; Gaensler et al. 2001). In this paper we report the results obtained from a *Beppo*SAX observation of 1RXS J170849–400910 that took place before the "glitch"–like event detected by *Rossi*XTE. A two–component spectrum, i.e. a power–law plus a black body, was found. Moreover the *Beppo*SAX observation revealed significant energy–dependent pulse profile. Pulse phase spectroscopy shows that, in the context of the blackbody plus power law spectral decomposition, this effect is likely connected to a photon index variation. This observation therefore provided the first evidence for pulse phase–related spectral variations in an AXP. Implications of these results are also briefly discussed.

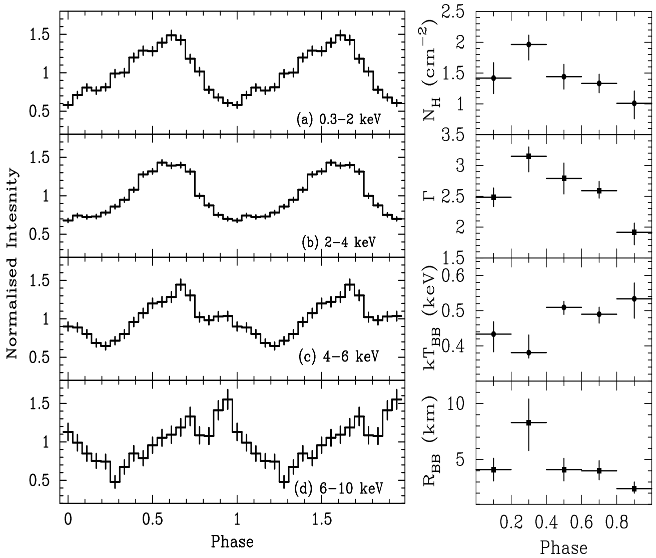

FIG. 1.— 1RXS J170849–400910 MECS and LECS light curves (left panels labelled from (a) to (d)) folded to the best period (P=10.99915 s) for four different energy intervals. For clarity two pulse cycles are shown. Zero phase was (arbitrarily) chosen to correspond to the minimum in the 0.3–2 keV folded light curve. The results of the pulse phase spectroscopy are shown for selected free parameters (right panels; the absorption column in units of 10^{22}). Phase intervals refer to those shown in the left panel.

2. OBSERVATIONS AND RESULTS

*Beppo*SAX observed 1RXS J170849–400910 between 1999 March 31 14:27 UT and April 1 22:50 UT with imaging Narrow field Instruments: the Low–Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997; 26 ks effective exposure time) and the Medium–Energy Concentrator Spectrometer (MECS; 1.3–10 keV; Boella et al. 1997; 52 ks effective exposure time).

2.1. Timing analysis

The arrival times of the 0.1–10 keV photons from 1RXS J170849–400910 were corrected to the barycenter of the solar system and a 1 s binned light curve was accumulated. The MECS counts were used to accurately determine the pulse period. The data were divided into 12 time intervals, and for each interval the relative phase of the pulsations was determined. These phases were then fit with a linear function giving a best–fit period of 11.99915±0.00002 s. The background subtracted light curves, folded at the best period in different energy ranges (Figure 1; left panels) show an energy–dependent profile. In particular the phase interval of the minimum in the energy interval 0.3–2 keV folded light curve corresponds to a maximum in the 6–10 keV folded light curve. Moreover the pulsed fraction (semi–amplitude of modulation divided by the mean source count rate) decreases from ∼40% to ∼30% from the lowest to the highest energy band.

2.2. *Spectral analysis*

PHA spectra were obtained from the *Beppo*SAX position (R.A. = $17^{\rm h}\,08^{\rm m}\,48^{\rm s}$, Dec. = $-40^{\rm o}\,08'58''$; equinox 2000; 90% confidence level radius of $22''$) of 1RXS J170849–400910 using an extraction radius of $4'$ and $8'$ for the MECS and LECS, respectively. Background subtraction was performed using both standard blank field exposures and background regions taken from the observation of 1RXS J170849–400910 far from the position of the AXP ending up with similar results. The PHA spectra were rebinned in order to have more than 40 counts in each bin such that minimum χ^2 fitting techniques could be reliably used. All those bins which were consistent with containing zero counts after background subtraction were rejected. Moreover the analysis of the MECS and LECS spectra was restricted to the 1.8–10 keV and 0.1–5 keV ranges, respectively, where the calibration of response files is more accurate. A constant factor free to vary within a predetermined range was applied in the fitting to account for known normalization differences between LECS and MECS.

TABLE 1

*Beppo*SAX PHASE AVERAGED FIT OF 1RXS J170849–400910.

Spectral Parameter	PL	PL + BB	BB + BB
N_H(10^{22} atom cm^{-2})	1.88±0.08	1.42±0.15	0.9±0.1
Γ	3.28±0.05	2.62±0.17	
PL flux	4.26	3.30	
$kT_{\rm BB}$ (keV)		0.46±0.03	0.50±0.02
—			1.54±0.06
BB radius (km)		4.0±0.4	4.4±0.2
—			0.30±0.02
BB flux		1.2	2.8+1.3
—			1.7
χ^2/dof	1.24	1.00	1.10
L_X (10^{35} erg s^{-1})	8.5	3.6	2.0

NOTES — Fluxes and luminosities refer to the 0.5–10 keV band ($\times 10^{-11}$ erg s^{-1}cm^{-2}. Fluxes are not corrected for the interstellar absorption. Flux uncertainties are about 10%. The source luminosities were derived by setting N_H = 0 and assuming a distance of 5 kpc.

A simple power–law model did not fit the data well (reduced χ^2 of 1.24 for 204 degrees of freedom, hereafter *dof*). All other single component models that we tried produced even worse results. A much better fit (see Figure 2) was obtained by including a soft thermal component, a blackbody, in addition to the power–law (reduced χ^2 of 1.00 for 202 *dof*). This model was successfully fitted to the spectra of three other AXPs. An F–test shows that the inclusion of the blackbody component is highly significant (probability of $\sim 6\sigma$). The best fit was obtained for an absorbed (N_H = (1.42±0.15)×10^{22} atom cm^{-2}) power–law with photon index Γ = 2.6±0.2 and a blackbody component with temperature of $kT_{\rm BB}$ = 0.46±0.03 keV (90% c.l. reported; see Table 1). The unabsorbed 0.5–10 keV flux was 1.3×10^{-10} erg s^{-1} cm^{-2}. The blackbody component accounts for about 36% of the total absorbed flux in the same band. Figure 2 shows the spectral shape and components of 1RXS J170849–400910 as determined by *Beppo*SAX. We also tried to fit the spectra using different spectral decompositions. Among these we find a relatively good fit (reduced χ^2 of 1.10 for 202 *dof*) with a two blackbody model (see Table 1). It is worth mentioning that also in this case we obtained a soft component (i.e. a black body) with a characteristic temperature similar to that inferred with the power–law plus black body model.

The data from the High Pressure Gas Scintillation Proportional Counter (HPGSPC) and the Phoswich Detector System (PDS) did not provide any useful information on 1RXS J170849–400910. In fact, due to the large FOVs of these instruments, the relatively short exposure time (∼25 ks), and steep spectrum of 1RXS J170849–400910 the source was not detected.

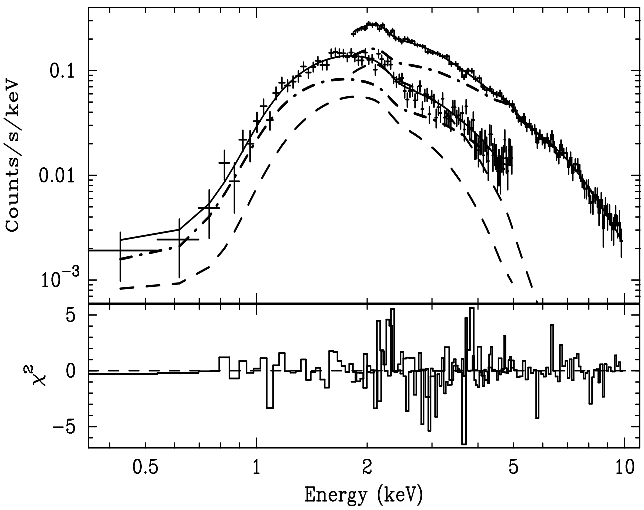

FIG. 2.— LECS and MECS energy spectra of 1RXS J170849–400910. The residuals (in units of χ^2) of the best fit are also shown (see the text for details). The power–law and blackbody components are shown with dotted–dashed and dashed lines, respectively.

2.3. *Phase resolved spectroscopy and pulse profiles*

Pulse phase spectroscopy (PPS) was carried out with the MECS and LECS data. A set of five phase–resolved spectra (phase boundaries 0.0, 0.2, 0.4, 0.6, 0.8) were accumulated. After rebinning and background subtraction these were then fit with the power–law plus blackbody model described in Sect. 3.1. Due to the small number of photons in the LECS spectra, we removed all the PHA channels below 1 keV. Initially, the blackbody temperature was fixed at its phase–averaged best–fit value and only the power–law parameters and blackbody normalisation were allowed to vary giving a cumulative (over the whole set of spectra) reduced χ^2 of 1.10 for 466 *dof*. The fits were then repeated with the power–law component fixed and blackbody parameters free to vary resulting in a reduced χ^2 of 1.32 for 466 *dof* for the best fit. Then all the parameters were varied and fitted together. In the latter case the best fit gave a reduced χ^2 of 1.04 for 456 *dof*. An F–test shows that the freeing of the blackbody and power–law phase–averaged parameters is highly significant (the reduction in χ^2 has a formal probability of 9×10^{-4} and 1×10^{-19} for the blackbody and power–law parameters, respectively). In Figure 1 (right panels) and 3 the results of the PPS are shown for the most interesting parameters and phase intervals.

A check was performed by fitting the power–law photon index values obtained in each phase intervals with a constant (see right panels of Figure 1). This set a $\sim3\sigma$ significant variation in the power–law photon index parameter. Statistical uncertainties prevent a firm detection of variations in the other parameters (see right panels of Figure 1).

The upper two panels of Fig. 4 show the pulsed fraction versus energy during *Beppo*SAX observation for the first two harmonics. These values were obtained by fitting the corresponding light curves with two sinusoidal functions. Note that definitions of the pulsed fraction which involve the maximum and the minimum of the folded light curve should be used with care as they are dependent on the binning time and, therefore, the presence of unusually low or high data points. The sinusoidal fit, when feasible, is less sensitive to these data points. The first harmonic decreases from $\sim$36% to $\sim$26% as the energy increases from 0.5–2 keV to 6–10 keV. A constant value of $\sim$10% is inferred for the second harmonic. The last two panels refer to the ratio between the power–law and the total absorbed fluxes (i.e. the blackbody plus power–law spectral model; third panel), and the ratio between the blackbody and the power–law unabsorbed fluxes (lowest panel). From the comparison of these quantities we can infer that: (i) there is evidence for a decrease of the 1*st* harmonic pulsed fraction at energies above 5 keV, although the statistics are poor; (ii) there is evidence for an anti–correlation between the power–law component and the 1*st* harmonic pulsed fraction (see first and third panels), and (iii) evidence for a direct correlation between the latter and the blackbody component (see first and fourth panels).

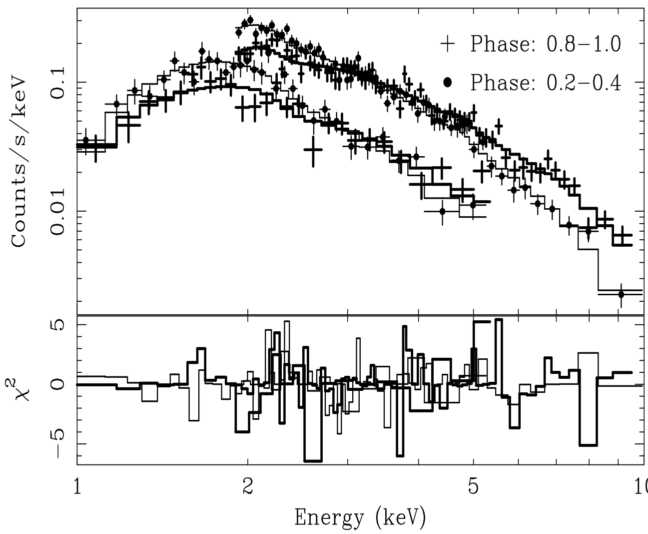

FIG. 3.— LECS and MECS spectra of 1RXS J170849–400910 for two selected phase intervals (0.2–0.4) and (0.8–1.0) as reported in Figure 2. The power–law photon index variation is clearly evident.

3. DISCUSSION

The *Beppo*SAX spectrum of 1RXS J170849–400910 is well modeled by the sum of a (absorbed) relatively steep power–law and a low–energy blackbody. Therefore 1RXS J170849–400910 is the fourth AXP, after 4U 0142+614 (White et al. 1996; Israel et al. 1999b), 1E 2259+586 (Corbet et al. 1995; Parmar et al. 1998) and 1E 1048.1–5937 (Oosterbroek et al. 1998), for which such a spectral decomposition has been detected. We note that these sources are also the ones for which good spectral data are available. This possible decomposition for 1RXS J170849–400910 was first suggested by Sugizaki (1997) although not statistically significant using the ASCA data. The comparison between the *Beppo*SAX and ASCA observations reveal that the source has remained nearly at the same (absorbed) flux level ($\sim4.4\times10^{-11}$ erg cm^{-2} s^{-1} and $\sim4.3\times10^{-11}$ erg cm^{-2} s^{-1} in the 0.8–10 keV band for *Beppo*SAX and ASCA, respectively). Also the spectral parameters (in the blackbody plus power–law model) are similar to those found by ASCA with the exception of the temperature of the blackbody which is higher in *Beppo*SAX: this is not unusual as *Beppo*SAX instruments have a higher sensitivity below 1 keV allowing a better evaluation of the absorption column and, therefore, of the blackbody component parameters.

We also tried to fit the spectrum of 1RXS J170849–400910 with other models. Among these we used two blackbodies.

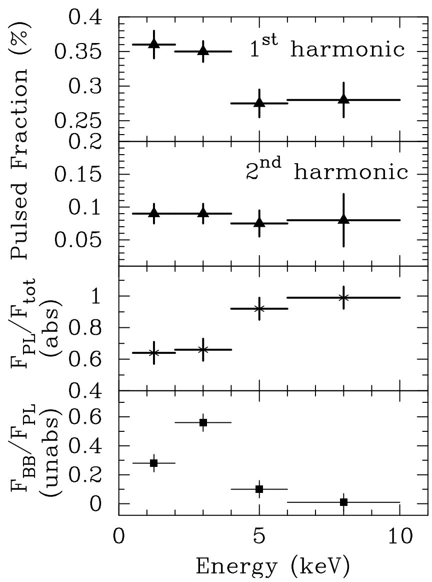

FIG. 4.— Pulsed fraction of the first two harmonics of 1RXS J170849–400910 as a function of the energy (upper two panels), together with the power–law to total absorbed flux ratio and the blackbody to power-low unabsorbed flux ratio (lower two panels). See text for details.

Such a decomposition is in agreement with accreting, magnetic field decay and cooling models which have been invoked to account for the main physical mechanism(s) responsible for the X–ray emission of AXPs (see also Thompson & Duncan 1996 and Heyl & Hernquist 1997). Two (or more) concentric regions with different temperatures are in fact expected: the innermost corresponding to the polar caps of the neutron star (which is also the hottest) and a larger area around the magnetic caps characterised by a lower temperature (see also DeDeo et al. 2000; Özel et al. 2001; Perna et al. 2001). Regardless the origin of the emission from these regions, we note that the size of the blackbodies is always smaller than the neutron star surface, even for an unrealistic distance to the AXP of $\sim$15 kpc, with the smallest region (R_{BB} $\sim$0.3 km) being also the hottest (kT $\sim$1.5 keV). The results of a more detailed and systematic spectral and timing study of the AXPs observed by *Beppo*SAX will be reported elsewhere.

An analysis of the pulse shape of 1RXS J170849–400910 as a function of energy (in the 0.3–10 keV) reveals a prominent variation with the minimum at low energies corresponding to the maximum at high energies (see also Figure 1). Correspondingly, pulse phase spectroscopy detected a significant variation for at least one spectral component, the power–law photon index, as a function of phase. The peak in the pulse profile at highest energy also corresponds to the lowest value of the photon index, similar to what observed in accreting X–ray pulsars (Makishima et al. 1999 and references therein). Although energy–dependent changes in the pulse shape were already observed in the past for 4U 0142+614 (White et al. 1996; Israel et al. 1999b; Paul et al. 2000), the variations of 1RXS J170849–400910 are also accompanied by a nearly total phase reversal between the low and high energy band, and are likely due by a changing power–law slope (as suggested by Sugizaki et al. 1997). We note that, in the past, the lack of any conspicuous change in the pulse profiles as a function of energy and/or pulse phase–resolved spectra of AXPs was used to argue against the possibility that these sources are accreting X–ray objects. We finally note that the pulse fraction as a function of energy shown in Figure 4 is not in disagreement with that recently reported by Özel et al. (2001) which used a different definition of the fractional contribution (and assuming only one harmonic) to the pulsations.

1RXS J170849–400910 is so far the only AXP for which a sudden spin–up was observed (Kaspi et al. 2000). This was interpreted as a glitch similar to that observed in the Vela and other young radio pulsars. However, we note that glitches could in principle be detected also in accreting (spinning–down) X–ray sources with a sufficiently high magnetic field strength (in analogy with the known characteristics of radio pulsars) if they are in a low noise level phase, as indeed AXPs are known to be. A way to distinguish, in the near future, whether 1RXS J170849–400910 experienced a radio pulsar–like glitch or, perhaps, an accreting X–ray pulsar–like spin–up behavior would be to accurately monitor the period history after the event. We note that the lack of the recovery of the $\dot{P}$ value to the pre–event one (in contrast with the known behavior of glitches observed in radio pulsars) would argue against "magnetar" models, at least in the current formulation, while its detection might be not conclusive for any model (magnetar and accretion).

1RXS J170849–400910 is also the first AXP for which spectral changes as a function of pulse phase have been significantly detected. These spectral/timing properties make 1RXS J170849–400910 an especially interesting AXP to study. More sensitive and/or higher throughput observations of 1RXS J170849–400910 might yield important additional information on the spectral changes causing the pulse shape variations and extend the energy range over which the source is detected above 10 keV.

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